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A CMBR Measurement Reproduced: A Statistical Comparison of MSAM1-94 to MSAM1-92

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ABSTRACT

The goal of the second flight of the Medium Scale Anisotropy Measurement (MSAM1-94) was to confirm the measurement of cosmic microwave background radiation (CMBR) anisotropy made in the first flight (MSAM1-92). The CMBR anisotropy and interstellar dust emission signals from the two flights are compared by forming the sum and difference of those portions of the data with the same pointings on the sky. The difference data are consistent with a null detection, while the summed data show significant signal. We conclude that MSAM1-92 and MSAM1-94 measured the same celestial signal.

Subject headings: balloons — cosmic microwave background — cosmology: observations

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1. Introduction

Measurements of anisotropy in the Cosmic Microwave Background Radiation (CMBR) continue as a subject of considerable interest to the astrophysics community. Future anisotropy measurements on scales of $0.^\circ1$ to $1.^\circ0$ will discriminate among early universe models and determine fundamental cosmological parameters (e.g. Hu and White 1996, Knox 1995 and Jungman *et al.* 1995).

Measurements of anisotropy at angular scales near $0.^\circ5$ have been reported recently by Ruhl *et al.* 1995, Netterfield *et al.* 1996, Gundersen *et al.* 1995, and Tanaka *et al.* 1995. Wilkinson 1995 voiced a common concern when he pointed out that "there are plausible systematic effects at levels comparable with the reported detections." To address this concern the 1994 flight of the Medium Scale Anisotropy Measurement (MSAM1) observed the same field as the 1992 flight to limit the possibility of systematic sources of the signal.

Cheng *et al.* 1994 (hereafter Paper I) reported observations of anisotropy in the CMBR from the first flight of MSAM1 in 1992 (MSAM1-92). Cheng *et al.* 1996 (hereafter Paper II) reported the results from the second flight in 1994 (MSAM1-94). A conclusion of the latter is that while a quantitative comparison was pending, there was good qualitative agreement between the two flights in the double difference data set, and that agreement was inconclusive for the single difference data set. This Letter presents a quantitative comparison of the MSAM1-92 and MSAM1-94 data sets.

2. Instrument and Observations

The MSAM1 instrument has been fully described in Fixsen *et al.* 1996 (hereafter Paper III); only an overview is given here. It is an off-axis Cassegrain telescope with a 4-channel bolometric radiometer at the focus. The beamsize is $28'$ FWHM and is moved $\pm 40'$ on the sky by the nutating secondary. The radiometer has 4 frequency channels placed at 5.7, 9.3, 16.5, and 22.6 cm^{-1}. For these observation, emission in the lower two channels is dominated by the 2.7 K CMBR, while ~ 20 K interstellar dust dominates the two higher channels.

The instrument configuration was similar for the two flights, with changes made only to the warm signal electronics and the gondola structure. These changes are discussed extensively in Paper III; the modifications to the electronics improved the noise performance, while those to the gondola reduced sidelobe sensitivity. The original superstructure had a large reflecting area above the beam, from which earthshine could potentially diffract into the beam. For the second flight, the gondola was suspended by a cable system which

reduced the far-sidelobe response. The measured near sidelobe response dropped from $-55\,$dB in 1992 in the worst case to less than $-75\,$dB in all cases in 1994.

As described in Papers I and II, the observed field is two strips at declination $81\overset{\circ}{.}8 \pm 0\overset{\circ}{.}1$, from right ascension $15\overset{\mathrm{h}}{.}27$ to $16\overset{\mathrm{h}}{.}84$, and from $17\overset{\mathrm{h}}{.}57$ to $19\overset{\mathrm{h}}{.}71$ (all coordinates are J1994.5). Fig. 1 shows the weighted beam centers of the fields observed in the 1992 and 1994 flights. A CCD camera is used to determine absolute pointing for both flights. The final accuracy of the pointing determination is $2\overset{\prime}{.}5$, limited by the gyroscope signal interpolation. This $2\overset{\prime}{.}5$ uncertainty is small compared to the size of our beam ($28'$) and the bins ($14'$) used below, ensuring adequate alignment of the two datasets.

During both flights Jupiter was observed to calibrate the instrument and map the telescope beam. Beam maps and calibrations are done separately for the two flights. The shape of the beam map is determined to 4% of the maximum amplitude. Random noise in the gyroscope system contributes 3.5%, and cosmic rays striking the detectors contribute 1.5%. Also, the choice of smoothing algorithm causes a 1.5% systematic effect. Combining this 4% error from each flight gives a 5.8% relative calibration uncertainty. The uncertainty in Jupiter's intrinsic brightness leads to an additional systematic uncertainty of 10% for the results of each flight; however, except for possible time variations in Jupiter's brightness which we do not expect, this uncertainty does not contribute to the comparison of the two flights discussed here.

3. Reanalysis of 1992 Data

The analyzed data sets reported in Papers I and II cannot be directly compared for two reasons: 1) the boundaries of the sky bins are different, and 2) the analysis reported in Paper I neglects correlations introduced by the removal of the small offset drift. The 1992 data is reanalyzed to account for these correlations, using a procedure nearly identical to that of Paper II. The 1994 data is also reanalyzed, with differences from the original analysis noted in the text below. Here we first review the Paper II analysis, then note the differences between that and the reanalysis used here.

First, the cosmic ray events are removed from the time stream. Cosmic ray removal techniques are different for the two years, and are discussed in Papers I and II. The data are then analyzed in a manner that provides sensitivity to two different angular scales on the sky. This is done by weighting the the time stream, S_i, with one of two demodulation templates, d_i, giving one "demodulated data point", $\Delta T_{cycle} = \sum_i d_i S_i$, for each full cycle of the secondary mirror movement. The "single difference demodulation" weights the

secondary-left data positively while weighting the secondary-right data negatively, giving a ΔT equal to the difference between the left and right temperatures. The result is a two lobed beam pattern on the sky with $80'$ beam separation. The "double difference demodulation" weights the secondary-centered data positively, while weighting the secondary-left and secondary-right data negatively, giving a ΔT equal to the difference between the center and the side temperatures. This produces a three lobed beam pattern on the sky, with $40'$ beam separation. The single difference and double difference data are nearly statistically independent.

A linear model is fit to these demodulated data including intensity for each sky bin and slow drifts in time. The noise used in the fit is estimated from the data. Both the time drift and noise estimate are described further below. The results of the linear fit are signal amplitudes for each sky bin with their associated covariances.

A spectral model for each sky bin consisting of CMBR anisotropy plus emission from 20 K Galactic dust, with emissivity proportional to frequency to the 1.5 power, is fit to all four frequency channels of binned sky data. The results of this spectral fit are the intensity of a "DUST" component and a "CMBR" component in each sky bin. The differences between the Paper II analysis and that done for this paper follow.

This analysis uses a $0\overset{\circ}{.}24$ bin size, double the size used in Paper II, which corresponds to the size of the central beam plateau. Angular orientation bins, which account for sky rotation relative to the secondary chop axis, are 20°, also double the previous size. The weighted beam centers of the identical bins are shown as filled symbols in Fig. 1.

The noise estimates are formed from demodulated data. This is a change from Paper II, where the estimate is made after after having removed the drift model. The noise estimates are made separately for each minute of data by measuring the rms of the demodulated data in that minute. The new noise estimate is used in reanalyzing both the 1992 and 1994 datasets. True sky signals make a negligible contribution to this rms estimate over these short time scales. This change has no substantial effect on the results of this Letter.

Also, in Paper II the drift model included terms based on gondola sensors (air pressure, and the pitch and roll angles of the gondola outer frame). This model was used in the 1994 reanalysis, while it was not used for the 1992 reanalysis. Instead, the original model for the drifts described in Paper I, a spline with knots every 2.5 minutes, was used.

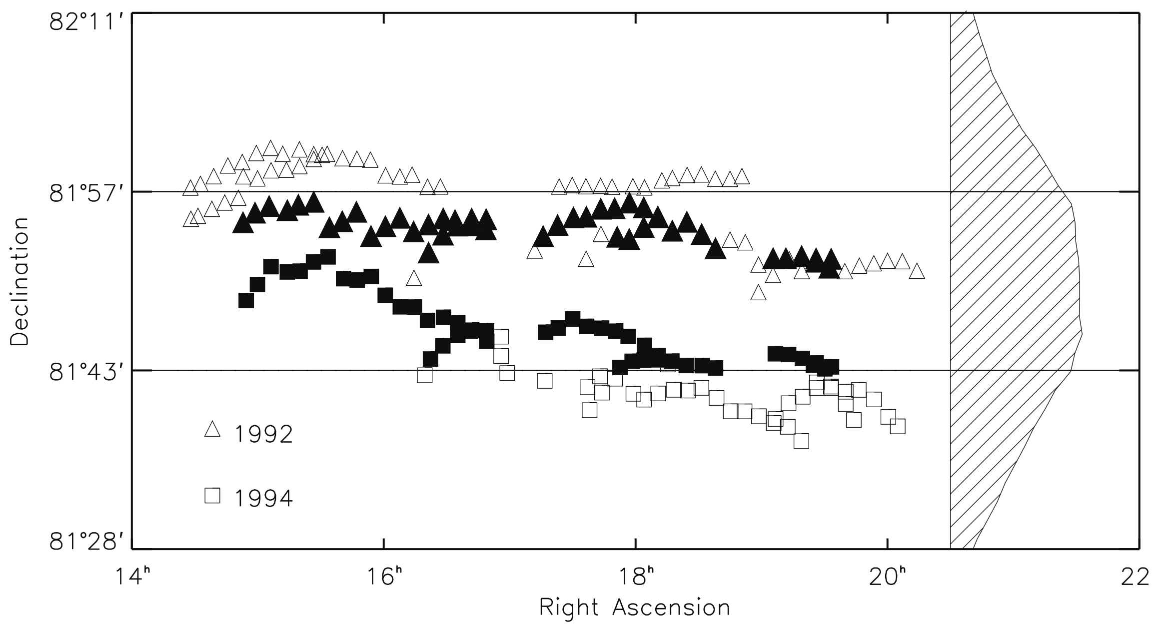

Fig. 1.— The weighted positions for each sky bin for both years. The triangles mark the 1992 centers and the squares mark the 1994 centers. The declination scale has been greatly expanded relative to the RA scale in order to see the detailed pointing differences. The filled symbols are the weighted centers for the bins used in the comparison ($\langle\delta\rangle = 81°50'$). The bin boundaries (every $0\overset{\circ}{.}24$, or $0\overset{\mathrm{h}}{.}11$) in RA are not shown. The declination bin boundaries (every $0\overset{\circ}{.}24$) are marked by the horizontal lines. The angular orientation is ignored in this plot, but is not in our analysis. The vertical beam profile is plotted in the hatched region. Note that at this declination, every hour of RA corresponds to about 2°.

4. Comparison

We compare the signal measured at each point on the sky as measured in the two flights, not just the rms levels of the sky signal found in each data set. In the 1994 flight, we attempted to observe the identical swath of sky observed in the 1992 flight. As can be seen in Fig. 1, which is extremely enlarged in declination relative to right ascension, the 1994 flight was low by about $10'$. To enable direct comparison, only the data from those bins which fall into the center declination bin is used. After this selection $\sim$50% of the data is retained. The data from the 1992 flight is differenced from that of the 1994 flight to form a difference data set, *92−94* . Similarly, the two data sets are summed to form a sum data set, *92+94* . This is done for each demodulation and for both CMBR and DUST. To allow for differing offsets in the two flights, a weighted mean is removed from each dataset. The covariance matrix, V_{ij}, for both the sum and difference sets is the sum of the masked 1992 and 1994 covariance matrices. There is no cross term because the flights have independent noise. The significance of any detected signal in the sum or difference is tested with a χ^2 statistic,

$$\chi^2_{\pm} = \sum_{ij} (\mathit{92} \pm \mathit{94})_i V^{-1}_{ij} (\mathit{92} \pm \mathit{94})_j.$$

The χ^2 and degrees of freedom, and the cumulative probability, $P(\chi^2)$, for the comparison is shown in Table 1. P is the probability of getting a value of χ^2 at or above the observed value, under the assumption that there is no signal in the data. This should be the case for the difference data, where the common sky signal should cancel.

To check the effect of the relative calibration uncertainty on χ^2, the 1994 dataset is rescaled by $\pm 6\%$ and the value of χ^2 recalculated. In all cases $|\Delta\chi^2| \leq 2$.

A Kolmogorov-Smirnov (KS) test (Press *et al.* 1992) of the *92−94* probabilities (.04, .22, .41, and .91) gives a 74% probability that these are drawn from a uniform distribution from 0 to 1. Based on this, we conclude that the *92−94* data in both the single and double difference demodulations for both the CMBR and DUST components is consistent with no observed signal.

A KS test of the *92+94* probabilities (2×10^{-12}, 2×10^{-8}, 4×10^{-7}, and 1×10^{-4}) gives a 7×10^{-4} probability that these are drawn from a uniform distribution from 0 to 1. From this, together with the extremely low χ^2 probabilities themselves, we see that there are statistically significant signals in all four *92+94* datasets. This result, combined with the absence of such signals in the *92−94* datasets, enables us to conclude that the signals observed during the two flights are common, and therefore present on the sky.

Table 1. Comparison of 1992 and 1994 Data Sets

Type	Data Set	χ^2/DOF	P
	Single Difference		
CMBR	*92–94*	52 / 45	0.22
	92+94	89 / 45	1×10^{-4}
DUST	*92–94*	47 / 45	0.41
	92+94	145 / 45	2×10^{-12}
	Double Difference		
CMBR	*92–94*	33 / 45	0.91
	92+94	118 / 45	2×10^{-8}
DUST	*92–94*	63 / 45	0.04
	92+94	109 / 45	4×10^{-7}

5. Conclusions

The same region of the sky was observed in the 1992 and 1994 flights to confirm the detection of a celestial signal. It is clear from the statistical analysis that the same sky signal is measured in these two flights. We conclude that at the level of our signal, our measurements are likely to be free from significant contamination from time-varying systematics such as sidelobe pickup or atmospheric contamination.

In addition to our own confirmation of the MSAM1-92 results, the Saskatoon experiment has recently observed this section of sky at lower frequencies, 36 GHz to 46 GHz (Netterfield *et al.* 1996). They have compared their signal with the double difference CMBR signal from Paper I, and find good agreement. This result, spanning nearly a decade in frequency, is strong evidence that we are observing CMBR anisotropies rather than some other astrophysical foreground source.

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